Human Performance Factors and Measures in Hull Form Selection

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ABSTRACT

High-speed (up to 30 knots) catamaran, trimaran, small waterplane area twin hull (SWATH), and Lifting Body type vessels have been built and tested to demonstrate technology for existing and evolving naval missions. A claimed advantage of these vessels is superior seakeeping in smaller ship sizes when compared to conventional monohulls capable of similar speeds. The effects of seakeeping qualities on human performance are an important consideration for hull form selection among these competing types. This is especially true when crew size reduction places a premium on the performance of each individual on board. The primary focus of this paper is a review of the development of technology for the assessment of human performance factors and measures in a vessel motion environment. Additionally, the paper briefly explores how two monohulls compare with a SWATH variant for one measure of human performance factors.

Human performance of various tasks may be characterized by a combination of effects. These effects include motion induced interruptions (MII), motion induced fatigue (MIF), cognitive performance, motion sickness incidence (MSI), and habituation. To illustrate how these factors might be used in hull form trade-off and design studies, a few results are presented for MII for two monohulls and a SWATH. Vessel motions are obtained from calculated information for the monohulls and at-sea trials information for the SWATH.

1.0 INTRODUCTION

1.1 Design Goal

This paper reviews progress in exploring the effects of hull form on human performance. Specific hull forms for some qualitative comparisons include two monohulls and one SWATH (small waterplane area twin hull). A relatively large database of computational analyses and experimental results exists to assess the seaway performance of monohull vessel designs. One example is presented by Baitis, Bennett, Meyers and Lee, reference [1], in which they discuss the seakeeping performance criteria for United States Coast Guard cutters similar to those shown in Figures 1, 2 and 3.

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Figure 1: US Coast Guard 47-foot Motor Lifeboat (MLB)

Figure 2: US Coast Guard 87-foot Coastal Patrol Boat (WPB)

Figure 3: US Coast Guard 110-foot Patrol Boat (WPB)

There is not a large database of computational analyses and experimental results available for other forms, such as SWATH vessels. The existing data are typically for point designs that are not easily compared with other point designs. Many of the vessels are private and their performance data is proprietary. Experimental studies and computational tools to predict motions of these vessels are under development and evaluation. However, these studies and tools have not yet achieved a level of maturity of confidence comparable to that for monohulls.

In order to demonstrate potential and generate data for verification of computational approaches, various experimental multi-hull and hybrid vessels have been built and tested. One example is the catamaran high-speed vessel X-CRAFT shown in Figure 4. This vessel is a new, high-speed catamaran that is scheduled for delivery to the US Navy in January 2005. Another example, shown in Figure 5, is the vessel SEA SLICE. SWATH technology was used with improved subsurface hull shapes to develop a relatively efficient, 30-knot vessel. For the latter, seakeeping trial results are presented in reference [2]. SEA FLYER, which is an example of a recently tested hybrid lifting body hull form (called Hybrid Small Waterplane Area Craft or HYSWAC), is shown in figure 6. This craft has achieved 30+ knots and has recently completed very successful sea trials that are expected to be reported by December of this year.

Figure 4: High-speed catamaran X-CRAFT

Figure 5: High-speed SWATH type vessel SEA SLICE

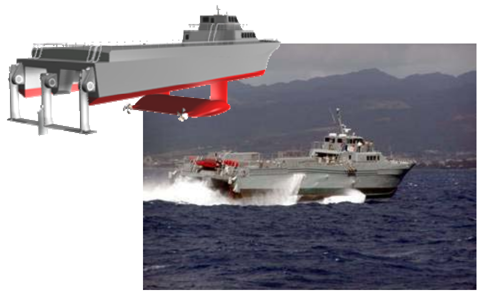

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Figure 6: Hybrid Small Waterplane Area Craft SEA FLYER

Figure 7: Canadian "Halifax" Class Frigate

Multi-hull, SWATH, and lifting body type hull form advocates claim to provide seaway performance superior to an equivalent, or even much larger, monohull. Thus, it is desirable to verify such claims by comparing the performance of these vessels with a range of monohulls. For this paper two convenient monohull designs were selected; the 82 foot Coast Guard boat pictured above and analyzed in reference [1], and a form similar to the Canadian frigate shown in Figure 7 and used to generate a worked example for seakeeping performance assessment in reference [3]. The SWATH variant SEA SLICE was selected to represent a multi-hull vessel. The lack of generally available computational methods for multi-hulls makes a full parallel comparison difficult. However, some trends in one aspect of human performance, Motion Induced Interruption (MII) are evident from examining trial data from the SWATH and comparing that data with computed predictions for monohulls.

Reference [3], NATO Allied Standardization Agreement STANAG 4154, Edition 3, outlines procedures for assessing seakeeping performance in the ship design process. Edition 3 took advantage of over 15 years of monohull ship design development to refine this approach to assessing seakeeping performance. To guide the assessment, generic criteria are presented for a wide range of mission equipment and human performance characteristics in the ship motion environment. Unfortunately, the designer of multi-hull vessels still faces the challenge of developing computational tools that will lead to fair comparisons of seakeeping performance to that of monohulls, or between multi-hull configurations, in as rigorous a fashion as presented in reference [3].

1.2 Approach

Given the challenge to incorporate human performance factors in vessels hull form decisions, this paper will address the following:

- A review of NATO IEG/6 Subgroup 5 on Seakeeping and follow-on efforts to identify factors that describe how the ship motion environment limits human performance,
- An assessment of the maturity in the research and development of each of the factors.
- A description of how the factors can be used in crew effectiveness assessments based on procedures outlined in NATO STANAG 4154, reference [3],
- Consideration of the relative effects of task location (vessel arrangements), and nature of tasks (physical, cognitive, etc.) on human performance in the motion environment,
- A discussion of additional work needed to fully characterize human performance factors,

- A brief, qualitative illustration of one aspect of an assessment with sample data from monohull (computed) and SWATH (experimental) motion data,
- A discussion of the importance of developing tools needed to accurately predict, and fairly compare, the ability of a range of vessel hull forms and configurations to achieve the best human performance.

2.0 DISCUSSION

What follows is a discussion of the state of development of human performance technology, sample applications of the technology for vessel evaluation, and discussions of further thrusts in the development of human performance technology.

2.1 History and Status of Human Performance Technology

During the 1986 NATO NG/6 Subgroup 5 meeting it was revealed that the navies represented experienced difficulty characterizing crew performance during design tradeoff studies. Subsequent meetings provided the realization that a small group of naval engineers could not effectively pursue defining ship motion effects on the crew. The group understood the mechanics of accelerations that caused a person to stumble, but could not understand physiological and mental implications and effects. To remedy this situation, behavioral scientists from what is now the University of New Orleans National BioDynamics Laboratory (NBDL) were invited to an American, British and Canadian (ABC-17) Warship Operability Workshop in Halifax in late 1989. A splinter group at the 1990 NATO meeting produced plans to initiate an experimental program in the Ship Motion Simulator at NBDL. The Dutch subsequently joined with the Americans, British and Canadians to form an ad-hoc, four-nation working group of naval engineers, medical doctors and behavioral scientists. The working group met every six months.

The working group established that ship motion effects on human performance could be defined in terms of these five factors:

MII - motion induced interruptions,
MIF- motion induced fatigue,
Cognitive performance,
MSI-motion sickness incidence, and,
Habituation

Many different shipboard activities may be subject to MII. Events as simple as slipping or stumbling and taking corrective action can significantly degrade human performance of many shipboard tasks. It is harder to work in a motion environment. Fatigue results and performance becomes degraded. As to cognitive performance, motion affects a variety of mental and psychomotor skills in ways that vary considerably between individuals. Motion sickness affects the performance of different people in different ways and can be debilitating. However, people do grow accustomed to the motion environment. This is called habituation.

Over the wide variety of shipboard tasks performed by humans these factors combine in different ways. The aim of the ad hoc working group was to develop a definition of each of these factors to establish a representative set of tasks, and to incorporate them in processes and procedures of practical use in ship design and hull form trade-off studies.

The ad hoc working group focused its initial efforts on advancing the characterization of motion induced interruptions (MII). Pioneering work by Baitis, Applebee and McNamara in the early 1980's revealed that performance of the flight deck crew on a frigate could be characterized by MII. See reference [6]. In 1990 the NBDL was chosen by the ad hoc working group to perform the first phase of experiments relating to the MII factor. The facility has a ship motion simulator which is capable of +/- 3.4 meters of heave and +/- 15 degrees of roll and pitch motion. See Figure 8.

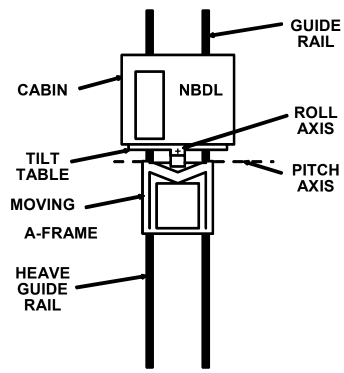


Figure 8: UNO National BioDynamics Laboratory Ship Motion Simulator (NBDL)

Since the NBDL was a US Navy facility in 1990, Navy volunteers were recruited to perform a variety of tasks in a simulated ship motion environment. They worked inside a 2.4x2.4 meter moving cabin. No attempt was made to draw subjects with specialties from the fleet. The volunteers were each individually and specifically trained to do the tasks to be evaluated.

The first set of experiments at NBDL measured motion induced interruptions of physical tasks. Simulated motion time histories for a frigate in bow and quartering seas were used to drive the motion simulator. Each subject was asked to perform and repeat a sequence of tasks - stand facing aft, position a weight on the wall, lift a Styrofoam cylinder, walk port to starboard, and stand facing port.

Follow-on experiments were performed at a similar facility in Bedford, England. The Bedford Motion Simulator added yaw and sway motion that enhanced the realism of the environment. Other experiments were performed in the ship motion simulator at the TNO Human Factors Research Institute in the Netherlands. The Dutch simulator has motion capabilities similar to those of NBDL, with the exception of heave motion being more limited.

Analysis of the experimental results led to a reasonable definition of MII for a range of simple manual tasks. Algorithms were developed to determine MII as a function of motion at any location aboard ship.

TNO also performed experiments to measure fatigue effects. The amount of effort put into a physical task is roughly measured by the intake of oxygen. A curve was developed to show how long the subject continued to work at each level of effort. This does not address how much rest is needed before the subject can return to work, nor does it measure what happens when the subject varies his or her work regimen. Some additional work has been done to answer these questions and to look at the effects of fatigue on performance of cognitive tasks. In recent experiments, TNO had two subjects in the moving cabin and asked them to alternate between physical tasks and performance of cognitive tasks while sitting at a computer. See reference [7].

Additional experiments were conducted at NBDL in 1993 and 1994 to determine the effects of ship motion on the performance of cognitive and fine motor tasks. See reference [8]. Subjects were exposed for 90 minutes to each of two frigate motion time histories. Some tasks were found to be affected by the motion. Others were not, though it was not known if any of these would be affected during longer exposure. A cooperative effort between the Institute for Naval Medicine in the UK and the TNO Human Factors Research Institute was initiated to answer these and other related questions. TNO has made some measurements during 72-hour exposures. NBDL is pursuing similar experiments. There is still much work to be done to capture the effects of motions on cognitive and fine motor tasks in a format useful for vessel design purposes.

The 1970's work by O'Hanlon, McCauley and others characterized motion sickness in terms of vertical acceleration in the frequency range of greatest human sensitivity, 0.167 HZ. Coincidentally, this is the same frequency range as the motion of many existing frigates and destroyers in Sea State 5. See reference [4]. They tested human subjects with different susceptibilities to motion sickness and varied exposure time. Human subjects were exposed to various levels of vertical acceleration at various frequencies.

The Canadians developed a family of curves for habituation based on the severity of weather when ships put to sea. Work performed by Dr. Tom Dobie, University of New Orleans, indicates that crew members can be trained or medicated such that they can remain effective through the first few days of a deployment and still be able to habituate. These procedures may reduce degradation of human operational capabilities prior to habituation to minimize any advantage that an adversary might have in the first few days of a deployment. While this work has direct application to operational considerations, additional work is needed to develop algorithms and criteria for application to design studies.

2.2 Criteria for Use in Ship Design

By 1997, as the revision to NATO STANAG 4154 on Common Procedures for Seakeeping in the Ship Design Process was being completed, the ad-hoc working group settled on a set of criteria. These criteria are listed in Table 1. The default values were those traditionally used for design studies. The group added motion sickness incidence and motion induced interruptions to the list, along with wind limits for the weather deck. Various researchers in the four nations have worked to more fully characterize fatigue effects but a specific criterion has not been established. The group continues to monitor progress, discuss findings, and recommend future work in modeling human and equipment performance and establishing improved criteria limit values for all factors.

Table 1: NATO STANAG 4154 Criteria for Human Performance at Sea

- Recommended Criteria
  - 20% MSI in 4 Hrs
  - 1 MII per Min
  - 35 Knots Relative Wind
- Default Criteria
  - 8 Deg SSA Roll
  - 3 Deg SSA Pitch
  - 0.4 G SSA Vertical Acceleration
  - 0.2 G SSA Lateral Acceleration
  - 35 Knots Relative Wind

2.3 Selection of Human Performance Factors for Design Studies

This section provides more detail about five factors for ship motion effects on human performance. One factor, MII, was chosen for the comparison between monohull and SWATH forms discussed in section 2.4 below.

2.3.1 MII

In 2000, Crossland and Rich presented a paper on a method for deriving motion induced interruption (MII) criteria. Reference [9] reported on the human performance tests performed in New Orleans and Bedford in 1993-95. Figure 9 shows an example of time histories used to determine when MII occurred. The instantaneous ratio of lateral to vertical acceleration is plotted against time. The vertical bars show where MII events occurred. Three of them occurred at positive or negative peaks; and the fourth when there was a surprise bump after a smaller peak.

Analysis of a number of records like this yielded reasonably averaged tipping coefficients to use as limits for simple tasks. See Table 2. For the initial tests at NBDL, lateral tipping coefficient was estimated to be 0.25; the tests yielded the value 0.23. Fore and aft tipping coefficient was estimated to be 0.17; the tests yielded 0.16. A more complete analysis of the data from New Orleans and Bedford yielded results for a wider range of manual tasks.

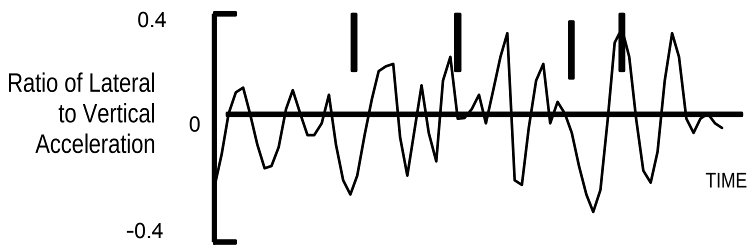


Figure 9: Example of tipping MII for a standing subject.

Table 2: Empirical coefficients found from force plate analysis.

Task	H5DOF	L5DOF	Average
Standing aft	0.232	0.254	0.243
Loading	0.162	0.178	0.170
Standing arms aloft	0.242	0.293	0.268
Walking on treadmill *	0.288	0.257	0.273
Standing athwart ship	0.133	0.178	0.156
Counting task*	0.250	0.233	0.242
All tasks	0.218	0.232	0.222

* Force plate analysis could not be used for the treadmill or counting task, because the subjects were not on the force plate. Empirical tipping coefficients for these tasks are taken from earlier analysis methods

Crossland and Rich also discussed risk levels, based on the number of MII encountered per minute, and related that to the effectiveness in performing the various tasks. See Table 3. The criterion adopted for NATO STANAG 4154 was one MII per minute.

Table 3: MII Risk Level

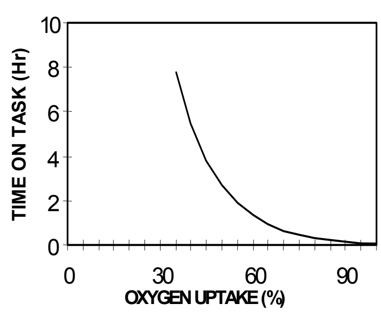
Risk Level	MII per minute (MII/min)
1. Possible	0.1
2. Probable	0.5
3. Serious	1.5
4. Severe	3.0
5. Extreme	5.0

The levels of acceleration are different at different locations on the ship, depending on how far each location is from the center of motion or center of gravity. Clearly, then, the occurrence of MII will depend upon location on the ship.

2.3.2 MIF

Figure 10 shows a sample of results from work done at TNO Human Factors Institute in the Netherlands on motion induced fatigue (MIF). The amount of effort put into a physical task is measured roughly by the oxygen intake. The curve indicates how long the subject can work at each level of effort. This says nothing about how much rest is needed before the subject can work again, nor does it measure what happens when the subject varies his or her work regimen. Some work has been done to answer these questions and to look at the effects of fatigue on performance of cognitive tasks.

Figure 10: Motion Induced Fatigue as measured by time on task



2.3.3 Cognitive and Fine Motor Tasks

The 1993 and 1994 NBDL experiments were designed to test the human abilities required to perform a variety of shipboard tasks performed during underway replenishment. Researchers used 41 tests to measure the motion effects on 21 human abilities that appear in different combinations in different shipboard tasks. See reference [8]. The 21 abilities fall into three categories; those which are purely cognitive, those which are visual and those which are psychomotor. The 41 tests were selected from a larger number which had evolved over the years since 1950. The tests have been used by different services to measure performance and to qualify military officers. The most appropriate were evaluated by the Battelle Memorial Institute in Columbus, Ohio, in a screening study. Those which could be administered in the moving cabin were evaluated in a pilot study that established the final 41 tests. An overall summary of the results is provided in Table 4.

Table 4: Summary of results from cognitive experiments

Categories of Abilities	Abilities Effected by Motion in 90 Minutes	Abilities not Effected by Motion in 90 Minutes
Cognitive	Deductive reasoning Memorization	Inductive reasoning Information ordering Reaction time Time sharing Written expression
Visual	Perceptual speed Spatial orientation	Flexibility of closure Response orientation Speed of closure Visualization
Psychomotor	Arm-hand steadiness Control precision Finger dexterity Multi-limb coordination Rate control	Manual dexterity Wrist-finger speed

This work did not establish how many abilities would be affected by motions during longer exposures where the effects of fatigue would start to play a role. A cooperative effort between the Institute for Naval Medicine in the UK and TNO's Human Factors Research Institute was initiated to answer this and other human performance questions. TNO has made some measurements during 72-hour exposures to the motion environment. NBDL is in the process of conducting similar experiments. There is still considerable work necessary to capture the effects fatigue on individual abilities and apply the knowledge to design.

2.3.4 MSI

Motion Sickness Incidence (MSI) was derived from measurements that O'Hanlon and McCauley obtained for the Office of Naval Research in the 1970's, reference [4]. A series of curves were developed for different exposure times and different percentages of the crew that were sick. The example shown in Figure 11 represents the statistical average for a four-hour exposure and 10% of the crew sick. These curves have been incorporated into ISO 2531on whole-body vibration, reference [5].

To initially set a single value for a motion sickness limit, the crew on destroyers and frigates were asked at what sea conditions these ships became uncomfortable, specifically when a portion of the crew became seasick. Investigators calculated and statistically averaged the vertical acceleration responses of these ships. They found that the ship acceleration curves for an average 0.2 g RMS (or 0.4 g SSA) had their maxima just touching the MSI limit curves. Later, when algorithms were available to compute MSI directly, 20% MSI in 4 hours was selected as a standard for ship design studies

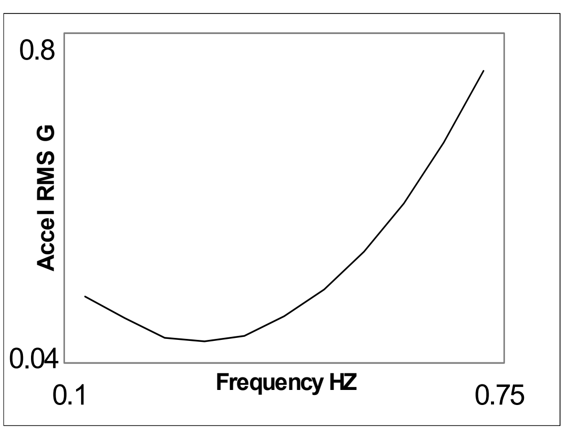


Figure 11: Motion Sickness Curve for 10% MSI in 4 Hours

2.3.5 Habituation

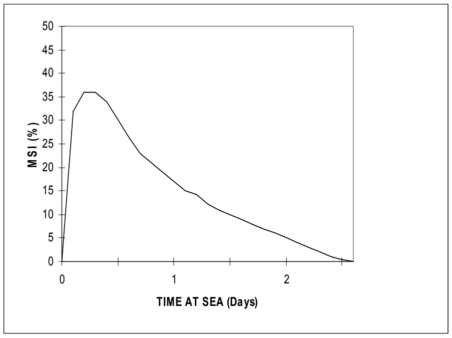


Figure 12: Motion Sickness and Habituation

Figure 12 provides an example taken from a Canadian Navy survey on how sailors felt within a few days of putting to sea in heavy weather. Additional work is needed to develop algorithms or guidance to apply these finding to design tradeoff studies.

2.4 Applications to Design Studies

2.4.1 Hull Configuration Evaluation

Vessels of particular interest are monohull, catamaran, trimaran, SWATH, lifting body, and hybrids capable of operating near 30 knots. For the purpose of this paper a qualitative look at the relative performance of two monohulls and a SWATH variant, entitled SEA SLICE, was pursued. SEA SLICE has a top speed of 30 knots and is 32 meters (105 feet) long with a displacement of about 183 tonnes (180 LT). The closest comparable monohull would have been the 110-foot U.S. Coast Guard ISLAND Class Patrol Boat (WPB) shown in Figure 3. It has a top speed of greater than 30 knots and a displacement of 156 tonnes (154 LT). However, the most comparable seakeeping data were available from reference [1] for the 82-foot Coastal Patrol Boat that has a top speed of 25 knots and is 25 meters (82 feet long) with a displacement of 73 tonnes (71.5 LT). The NATO Generic Frigate was chosen for comparison as it represents a large monohull and was used in reference [3] to illustrate the NATO standard seakeeping evaluation process. It has a top speed of 30 knots, is 125 meters (410 feet) long, and a displacement of 4,000 tonnes (3,940 LT).

Characteristics of the vessels shown in Figures 1 through 7 are listed in Table 5. The three that are highlighted were picked to illustrate evaluating of MII performance during hull configuration studies and to highlight the inherent differences between the SWATH and monohull forms.

Without analytic or computational prediction methods that can be employed with equal confidence for both monohulls and unconventional forms careful, systematic, and consistent comparisons cannot be performed. For the present effort, it is assumed that the computational predictions for the monohulls are accurate and representative of full-scale, at-sea performance. Neither computational nor experimental information were available for SLICE. Full-scale seakeeping test results were employed for this vessel. The SEA SLICE sea trials are summarized in reference [2]. The time histories used for the MII analysis were taken directly from individual trial run time histories. This limited the SEA SLICE information available for comparison.

Table 5: Characteristics of various vessels

VESSEL	US COAST GUARD CUTTERS			X-CRAFT	SEA SLICE	SEA FLYER	GENERIC FRIGATE
	47' MLB	82' WPB	110' WPB	--	--	--	NATO
	Reference [1]			--	Ref. [2]	--	Ref. [3]
TYPE	Monohull	Monohull	Monohull	Catamaran	SWATH	Hybrid Lifting Body	Monohull
Displacement (tonnes)	18	73	154	1,100	183	295	4,000
WL Length (meters)	13.1	23.8	31.7	73	31.7*	50	124.6
WL Beam (meters)	3.9	4.8	5.9	22	16.8	12.8	14.7
Draft (meters)	0.8	1.8	2.1	3.6	4.3	5.8	4.46

*Note: SLICE length is given as length overall

2.4.2 Seakeeping Performance Evaluation

Seakeeping performance of the NATO Generic Frigate is discussed first. The process was fully outlined in the NATO standard of reference [3] and illustrated in detail via a worked example for the frigate. The 82-foot U.S. Coast Guard boat is discussed next as it was evaluated in a similar fashion. The information for the 82-foot Coast Guard boat can be found in reference [1]. Lastly, a limited analysis of the high-speed SWATH type vessel SLICE, shown in Figure 5, is discussed. As reported in reference [2], the highest wave conditions encountered were 3.1 to 4.3 meters (10.3 to 13.8 feet) significant amplitude (high Sea State 4 to low Sea State 5).

2.4.2.1 Application of NATO Method

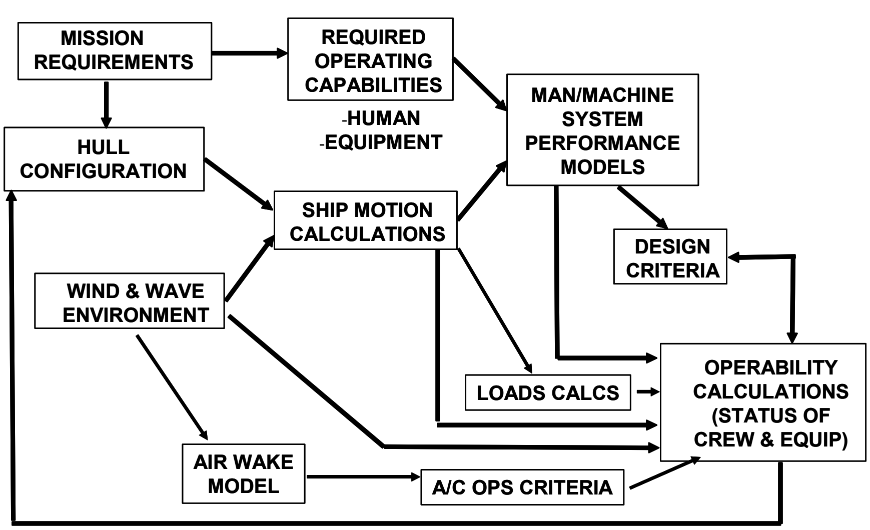


Figure 13: Seakeping in the ship design process

The NATO standard approach to seakeeping in the ship design process is shown in the block diagram of Figure 13. One of the missions of the generic frigate was assumed to be Transit and Patrol. The Required Operating Capabilities for this mission were used to derive the seakeeping criteria listed in Table 6 as applied to specific shipboard locations listed in Table 7.

Table 6: Seakeeping Criteria: Transit and Patrol Mission for NATO Generic Frigate

Parameter	Limit Value	
Roll Angle	4.0	RMS deg
Pitch Angle	1.5	RMS deg
Vertical acceleration	0.2	RMS g
Lateral acceleration	0.1	RMS g
Tipping MII	1.0	per minute
Deck Wetness Index	30	per hour
Bottom Slamming Index	20	per hour
Propeller Emergence Index	90	per hour

Table 7: Locations for evaluating seakeeping criteria on Generic Frigate

Parameter	Comments	X (m) (aft of FP)	Y (m) (+ Port)	Z (m) (above BL)
MII and accelerations	bridge at CL	26.2	0.0	14.8
MII and accelerations	helm (on bridge)	26.2	- 4.0	14.8
MII and accelerations	hangar top	84.1	0.0	16.0
MII and accelerations	flight deck	109.6	0.0	11.3
Deck wetness	0.10 L_{PP} aft FP	12.5	0.0	12.4
Bottom Slamming	0.15 L_{PP} aft FP	18.7	0.0	0.0
Propeller Emergence	25% emergence	116.5	± 3.0	1.07

The Hull Configuration block in Figure 13 is represented by the body plan shown in Figure 14, the characteristics listed in Table 5, plus the weight distribution and hydrostatic characteristics from which the natural roll period is derived. Sample wave statistics are shown in Figure 15 for the winter season averaged over the North Atlantic basin.

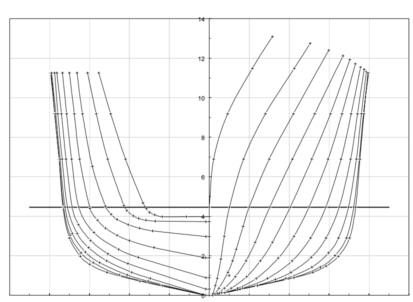


Figure 14: NATO STANAG 4154 worked example; body plan of Generic Frigate

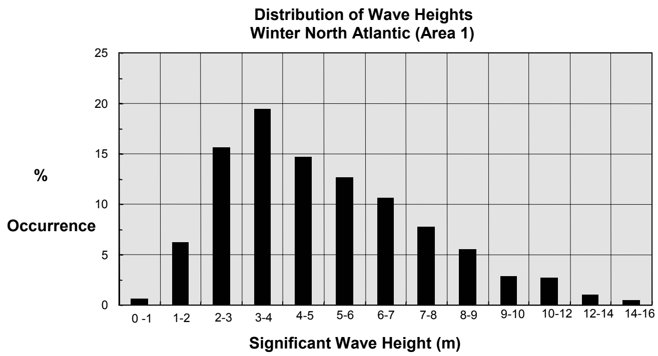


Figure 15: Sample environmental statistics for Generic Frigate operating area

For the range of sea conditions shown, ship motions are calculated for monohull type ships using a frequency domain, linear strip theory based computer program. The U.S. Navy standard ship motion program (SMP) described in references [14] and [15] is one that is used; the Canadian SHIPMO is described in reference [16].

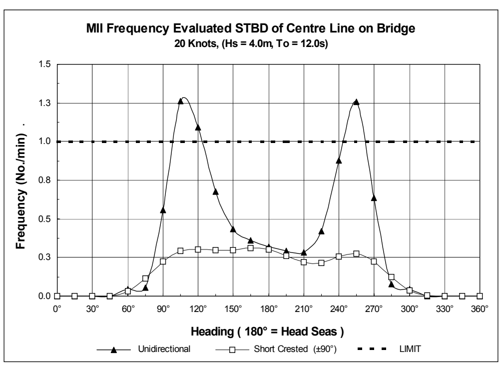


Figure 16: Sample (MII) on Generic Frigate; 20 knots ship speed, SS 5

A typical result of interest for this comparison is shown in Figure 16. There are two curves for motion induced interruptions (MII) for a ship speed of 20 knots into a Sea State 5. One curve is for commonly encountered short crested seas (spread around a predominant direction). The other curve is for long crested seas that are typically propagated from a distant storm. MII is shown as a function of heading. A dashed line is shown for the chosen limit of 1.0 MII per minute.

Seakeeping evaluation programs, such as the American SEP discussed in reference [17] and the Canadian SHIPOP discussed in reference [18] are used to compute the percent of time of operation (PTO), or the availability of the vessel to perform the specified mission in the specified operating area during the season of interest. As an interim step, operability envelopes are developed for each ship speed. A typical example is shown in Figure 17 for the Generic Frigate at 20 knots in short crested seas. Limiting significant wave heights are plotted as a function of ship heading relative to the seaway. Each heading lists the criterion from Table 6 that was first exceeded. This defined the limiting wave height for that heading. Note that tipping MII limits were reached on the flight deck, or in the hangar, in bow quartering, beam and stern quartering seas. Note also that ship motion criteria, other than those for human performance, set the limits at other headings. Specifically, bow slamming defines the limit in bow seas and roll motion defines the limit in stern seas. Operability envelopes for various ship speeds are shown in Figure 18. It should be noted that the controlling limit criteria are different for different ship speeds, and are thus not listed on this figure.

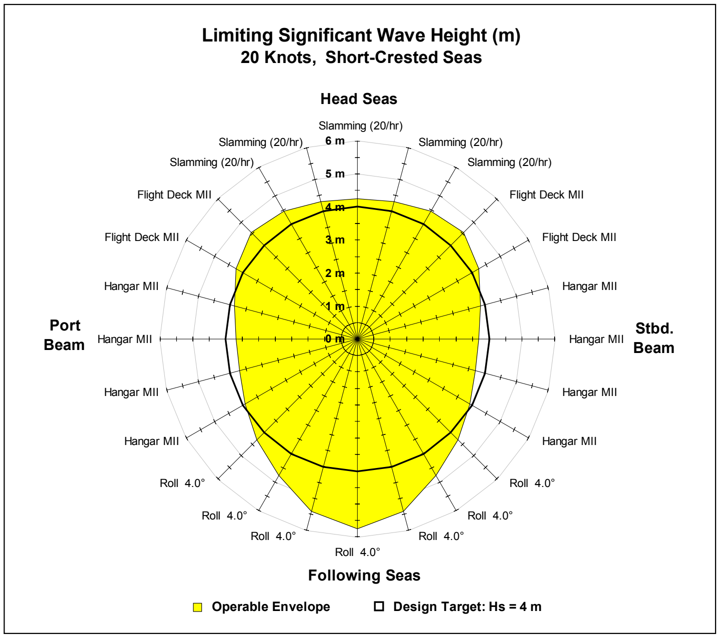


Figure 17: Sample Operability Envelope for the Generic Frigate; ship speed 20 knots, short crested seas

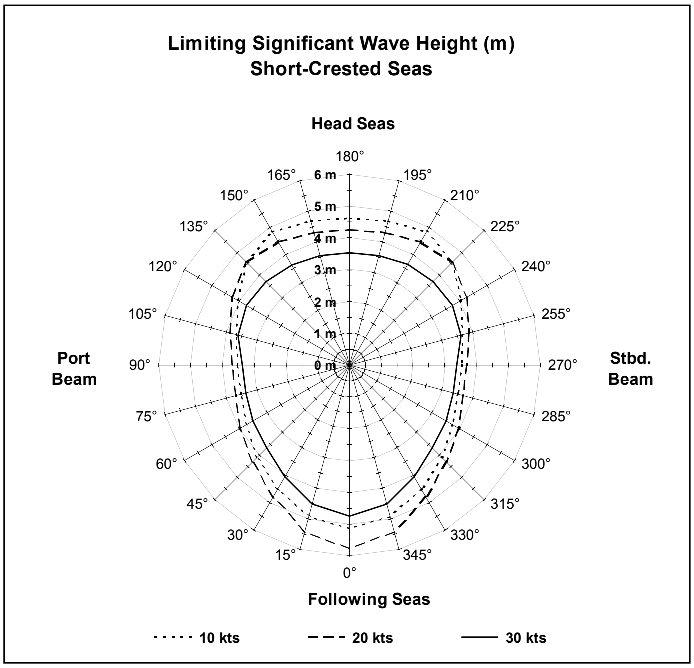


Figure 18: Sample Operability Envelope for the Generic Frigate; three ship speeds, short crested seas

Once the operability envelope is computed, the wave statistics for the operating area are used with a speed time profile to compute the PTO. The wave statistics are shown in Figure 15. The speed time profile for the Transit and Patrol mission is listed in Table 8. Sample results are shown in Figures 19 and 20. Figure 19 shows PTO versus heading for a ship speed of 20 knots into short crested seas in the winter in the North Atlantic. Figure 20 shows the corresponding weighted average for various ship speeds. Given the mission speed profile shown in Table 8, the MSP weighted average PTO for the Transit and Patrol mission is predicted to be 82.7 % in the North Atlantic in winter.

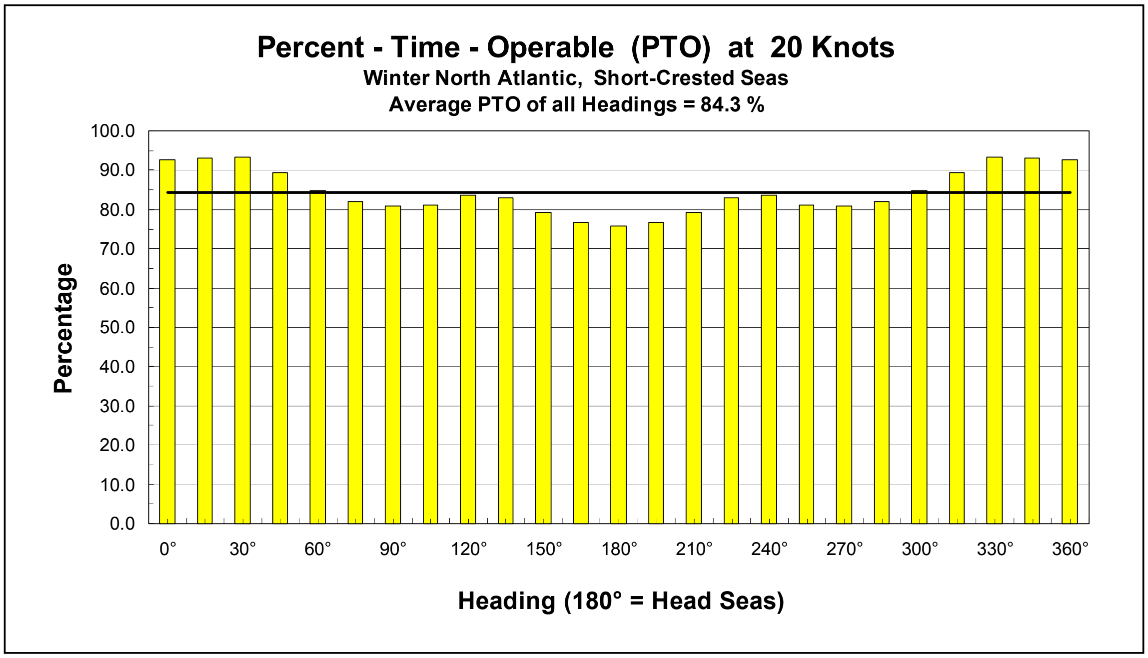


Figure 19: Sample percent time operable (PTO) for the Generic Frigate; ship speed 20 knots, short crested seas

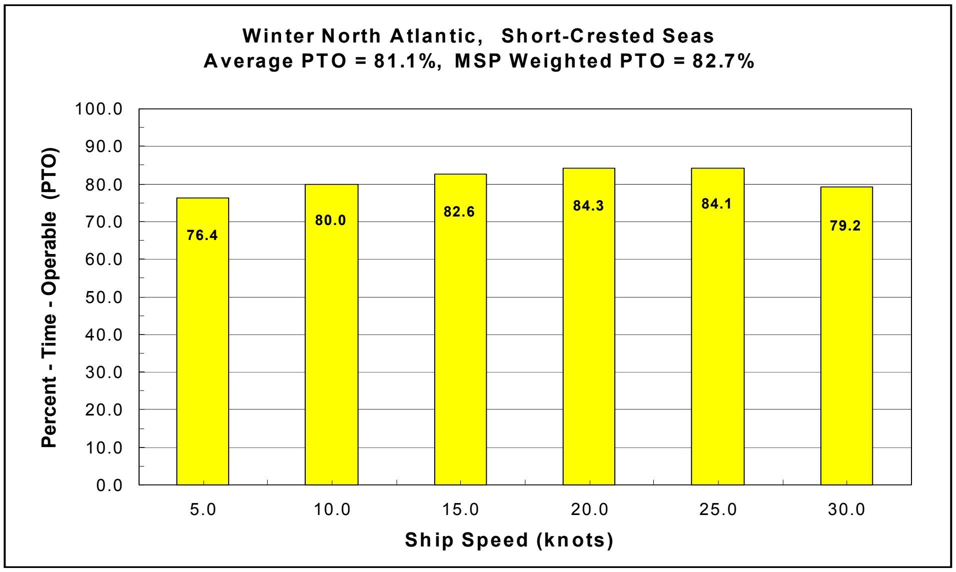


Figure 20: Sample heading-averaged PTO for the Generic Frigate; various ship speeds, short crested seas

Table 8: Mission Speed Profile (MSP) for the Generic Frigate

Speed (knots)	Percent of Time at Sea
5	6
10	12
15	32
20	42
25	7
30	1

The seakeeping performance of the 82-foot U.S. Coast Guard Coastal Patrol Boat employed SMP and SEP. Of particular interest was human performance at the boat handling station and in the pilot house. The seakeeping motion criteria and locations are listed in Table 9 and 10.

Table 9: Seakeeping Criteria for boat handling on 82-foot USCG Coastal Patrol Boat

CRITERION		APPLICABLE LOCATIONS
8	Degrees Roll, Significant Amplitude	Centre of Gravity
6	Degrees Pitch, Significant Amplitude	Centre of Gravity
20	Wetness per hour	Boat deck, starboard rail
30	Slams per hour	Bottom at Station 2
0.4	G's Vertical Acceleration, Sig. Amp.	Boat deck, starboard rail, and pilot house at helmsman's chair
0.2	G's Lateral Acceleration, Sig. Amp.	Boat deck, starboard rail, and pilot house at helmsman's chair
0.2	G's LFE, Significant Amplitude	Boat deck, starboard rail, and pilot house at helmsman's chair
2.1	Tipping Incidents (MII) per Minute	Boat deck, starboard rail, and pilot house at helmsman's chair
5	MSI % per 30 minutes	Boat deck, starboard rail, and pilot house at helmsman's chair

Table 10: Point locations on 82-foot USCG Coastal Patrol Boat

POINT	LOCATION		
	X	Y	Z
	Station number relative to forward perpendicular	Distance in meters off centreline (positive to port)	Distance in meters above baseline
Centre of Gravity	11.3	0	2.2
Bottom at Station 2	2	0	0.6
Boat Deck	15.4	-2.3	3.2
Pilot House	8.2	0	6.1

The operability envelopes for handling at the boat launch station and piloting the boat at 18 knots are shown in Figures 21 and 22. Note in both cases that the limit contours are asymmetric starboard to port. It is important to note that this is a function of the locations of various tasks aboard the vessel and the character of the seaway, which may also be asymmetrical.

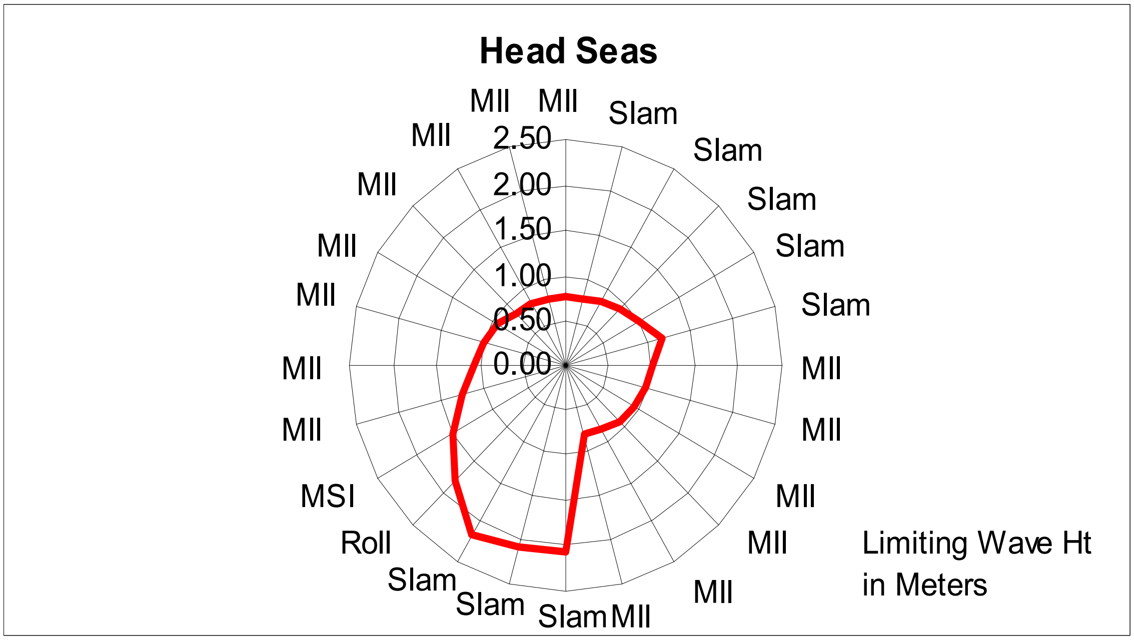


Figure 21: Operability Envelope for boat handling on the 82-foot USCG patrol boat; speed 18 knots, short crested seas

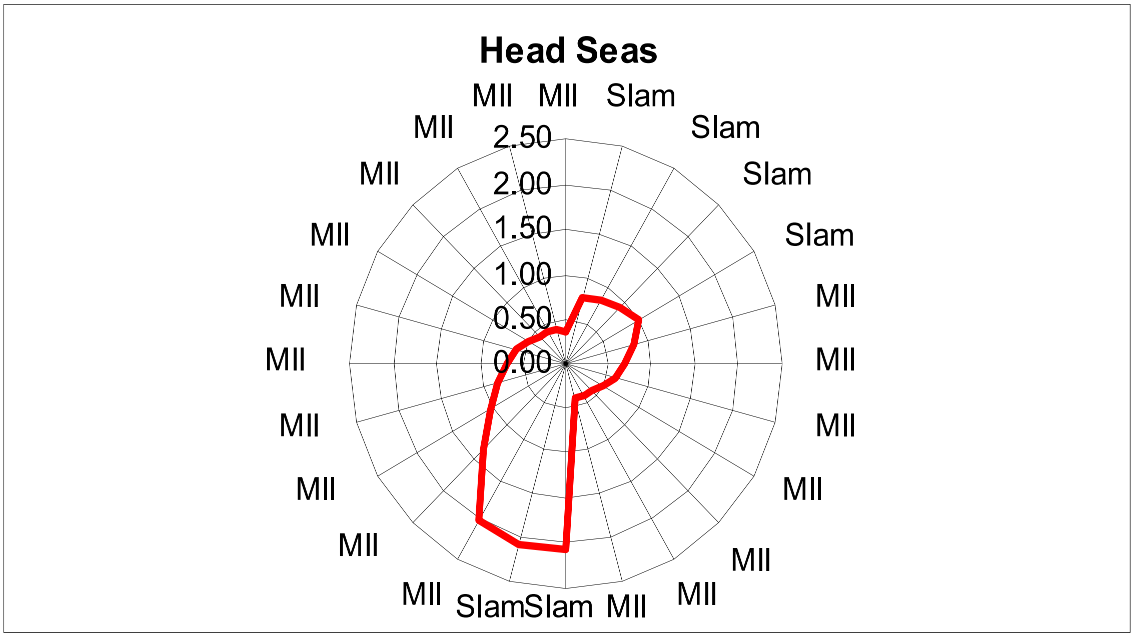


Figure 22: Operability Envelope for piloting the 82-foot USCG patrol boat; speed 18 knots, short crested seas

In both cases, MII is the limiting criteria for starboard beam, stern quartering and stern seas. With the sea on the port side, MII is the limiting criteria for beam, bow quartering and head seas. At other headings, other ship limits such as bow slamming are the limiting criteria.

To make a rough comparison with seakeeping performance of the Generic Frigate, the operability envelope for boat handling on the 82-foot USCG patrol boat is overlaid on that for transit and patrol on the frigate. See Figure 23. Note that the missions, and thus the seakeeping criteria listed in Tables 6 and 9, are different between the two vessels. The locations of mission functions listed Tables 7 and 10 are different. Additionally, the vessel speeds are different; 18 knots for the 82-foot USCG patrol boat and 20 knots for the Generic Frigate. Even so, this inexact comparison shows that the larger monohull (the frigate) is capable of operating in much heavier sea conditions than is the smaller one. This is not surprising as the size of the vessels is vastly different.

It should be emphasized that for actual design trade-off studies the missions, sea conditions, and vessel speeds should be kept the same between the different vessel designs, or design variants. The location of various functional areas on the ship could vary between designs and should also be accommodated for quantitative comparison studies.

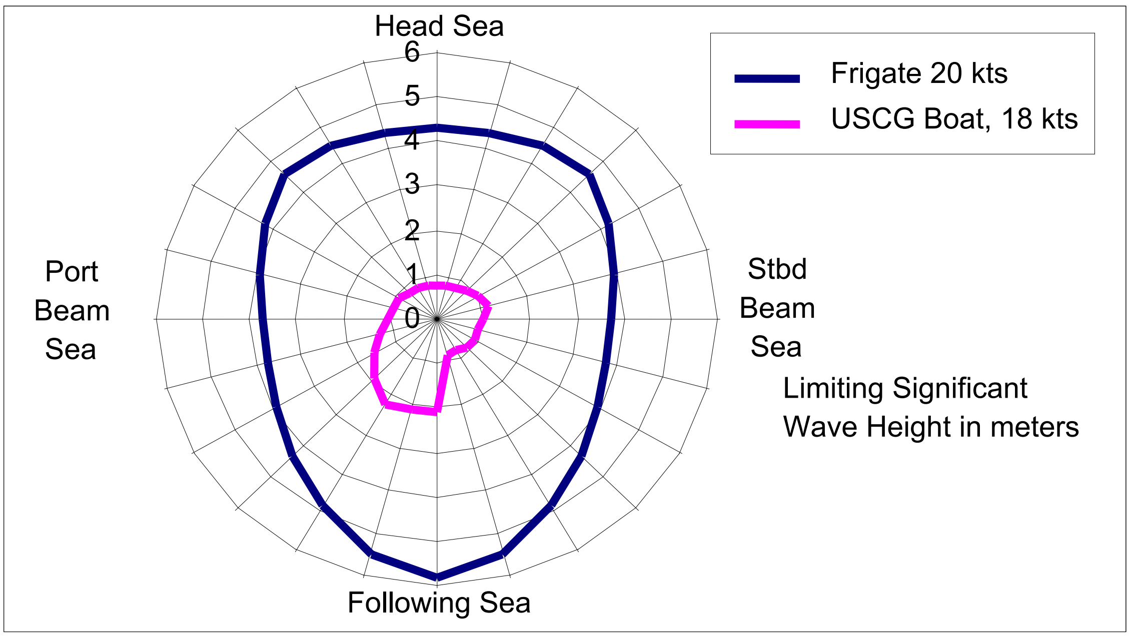


Figure 23: Rough operability comparison between the 82-foot USCG patrol boat and the Generic Frigate.

2.4.2.2 Potential Application in Multi-hull and Hybrid Hull Types

The NATO standard approach to seakeeping described above for monohull type vessels is proposed for use with multi-hull vessels and other non-monohull configurations. As a start, preliminary analyses have been done on motion data from sea trials on SEA SLICE.

All of the data for SEA SLICE were obtained in high 4 to low 5 sea states with very short periods (6.1 to 6.4 second modal periods). The significant wave heights ranged from about 2.5 to 3.3 meters (8.2 to 10.7 feet) double amplitude for the data runs evaluated for MII events. The analysis of SEA SLICE employed time histories of at-sea trial runs. These trials, but not the time histories of specific runs, are reported and

summarized in reference [2]. The accelerometers records for the runs evaluated for MII were located in the superstructure about 6 meters forward of the CG, on the centerline and immediately below the pilothouse. Vertical, longitudinal, and transverse accelerations were recorded. A total of eight runs were examined for MII and included head, port and starboard bow quartering, port and starboard beam, starboard stern quartering, and following seas. The formula used to indicate a MII event was the following:

$$LA= [(a_x)^2+(a_y)^2]^{1/2}$$

If $LA/(a_z+1)>TC$

A MII has occurred and the following 3 seconds were considered to encompass the event

Where:

LA= Lateral acceleration
a_x = Longitudinal acceleration
a_y = Transverse acceleration
a_z = Transverse acceleration
TC = Tipping Coefficient

For a TC threshold value of 0.243, which is a value used for typical monohull studies, not a single MII occurred during the SEA SLICE trials. The results indicate that SEA SLICE performs, with respect to MII, as well as the much larger monohull.

To check that there was not an error in the process, the TC threshold value was set at 0.11, 0.17, and 0.22 for two of the data records with the highest rms accelerations. Figure 24 indicates that a TC threshold value of about TC>0.17 would be required for 0.3 to 0.5 MII per minute. This indicates that MII/minute for this vessel is extremely low, at its worst heading (head and bow quartering), in a high 4 to low 5 sea state at 23 knots.

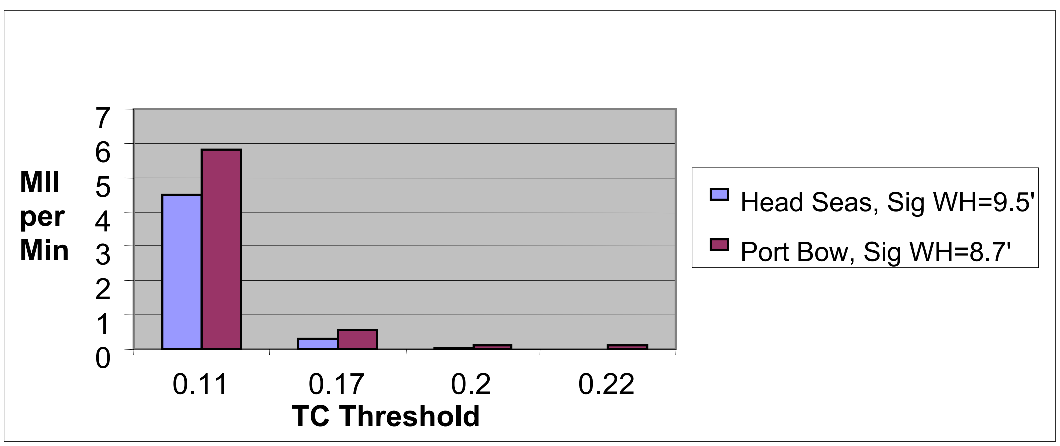


Figure 24: MII/min versus TC Threshold for SEA SLICE at 23 Knots

This correlates well with observations of trial personnel, who considered the comfort of the vessel remarkable. Based on this observation, operational limits in normal sea states are not likely to be governed by MII for SEA SLICE and similar vessels.

A rough comparison of the performance of SEA SLICE with that of the monohulls is illustrated by plotting the highest sea conditions that SEA SLICE encountered during sea trials on the operability contours for the two monohulls. See Figure 25. In trial run 53, listed in reference [2], SEA SLICE encountered starboard bow quartering seas of 4.27 meters significant amplitude. In run 57, Slice encountered starboard beam seas of 3.14 meters. For both of these runs the automatic ride control system was turned off. The runs, therefore, represent inherent performance for SEA SLICE. The two data points appear just inside the limit curve for the Generic Frigate. In neither run were MII criteria exceeded. This suggests that SEA SLICE may ride as well as the much larger monohull Generic Frigate, at least in terms of MII.

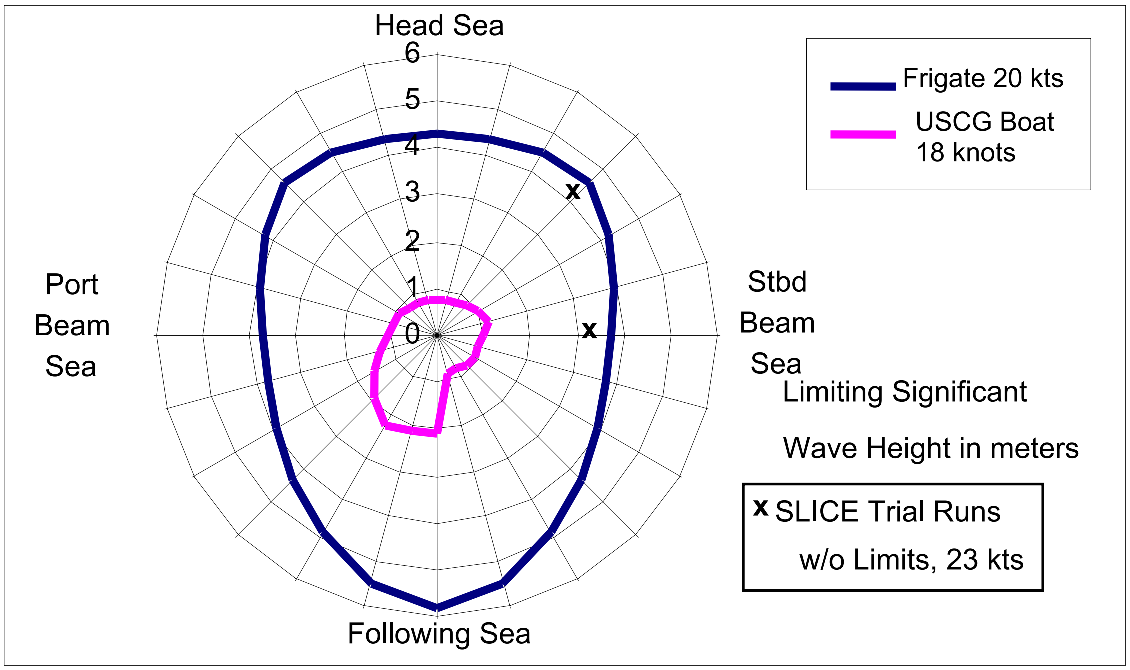


Figure 25: Operability contours for two monohulls with SLICE data points added

Based on reference [2], the limiting events during the SEA SLICE trials for head and bow quartering runs were slamming on the struts or bridging structure wet deck. For one bow quartering run, with a significant wave height of over 2.7 meters (9 feet), speed was reduced from 23 to 18 knots to alleviate slamming. Beam, following, and stern quartering seas produced notably small accelerations and a smooth ride at 23 knots in waves with a significant height of 4.2 meters (13.8 feet).

2.5 Future Development of Human Performance Technology

The beginnings of a new approach to seakeeping in the ship design process grew out of discussions in the 37th meeting of NATO Subgroup 5 on Seakeeping. The approach is shown in Figure 13 and discussed in reference [3]. This approach acknowledges the importance of the man/machine performance models and motion criteria as the links between the ship motion and operability calculations. The first steps have been taken toward better definition of human performance criteria with the development motion induced interruption models and criteria. The ABCD Working Group on Human Performance at Sea reported, in reference [12], on work being done to define the effects of ship motion on cognitive performance, including decision making.

Clearly, progress is being made on the characterization of shipboard tasks in terms of human abilities. These characterizations range from purely mechanical, to fine motor (psychomotor), visual, and purely cognitive abilities. Eventually, performance limits for each of the abilities may be overlaid to characterize specific shipboard tasks and to develop ship motion criteria to support evaluation of competing hull forms.

To help set the direction for continuing development of human performance and habitability models, NATO oversaw deployment of a Performance Assessment Questionnaire. The questionnaire was provided to six ships during exercises in the North Atlantic Ocean, off the coast of Scotland, in February 1997. Of 1,500 questionnaires handed out, over 1,000 were filled out and returned. Sailors performing a wide variety of shipboard assignments were asked to answer a series of questions at the end of each watch. The questions were formulated to provide indications of how ship motions affected their performance. In all, the returned questionnaires yielded 16,000 data sets which the Canadians analyzed. In Reference [12] Colwell presents his findings on the effects of motion sickness, motion induced interruptions, fatigue and cognitive degradations on the performance of a wide range of tasks and activities ranging from manual to decision making.

2.6 Future Vessel Design Trade-Off Studies

Much work remains to bring the seakeeping performance prediction technology for monohull and multi-hull type vessels to the same level of maturity. Progress is being made and it is important for NATO members to support such efforts within their countries. When an appropriate level of prediction capability for multi-hull and hybrid hull forms is demonstrated, trade-off studies can be performed with consistent conditions and constraints. At the present, trends can only be inferred and only limited comparisons can be made with model tests and limited at-sea data from large-scale demonstrators.

The roll of automatic maneuvering and ride control systems must be emphasized. Almost all modern high-speed craft, of all hull configurations, have automatic maneuvering and ride control systems. These systems can heavily influence seakeeping performance and must be included in prediction methods.

Several large scale demonstrator craft have been, or will soon be tested. The X-Craft, pictured in figure 4, is expected to complete trials early in 2005. SEA FLYER, pictured in figure 6, has just completed a comprehensive set of sea trials. These programs should provide excellent data for correlation with analytic and experimental methods employed in their design and should provide significant insight into the quality of those tools and methods. This data offers a great opportunity to assess the state-of-the-art of predictive tools while providing insight into characteristics of these advanced catamaran and lifting body forms.

3.0 CONCLUSIONS AND RECOMMENDATIONS

3.1 Conclusions

Based on the NATO work to develop seakeeping evaluation methods, computed predictions for two monohulls, and full-scale trial results for a SWATH variant, the following conclusions are offered:

3.1.1 The proposed NATO approach for human performance assessment appears reasonable to apply to a variety of hull forms as it considers multiple factors such as hull slamming and equipment motion limits. As such, the method should be fair and robust. Work remains in applying research in degradation of cognitive performance and fatigue factors to ship design and assessment studies.

3.1.2 Parity in computer prediction tools for monohull versus other hull forms is important for trade off studies in the future. Additionally, prediction tools should accommodate the effects of automatic ride control and maneuvering systems. These tools provide more conditions than full scale trials can yield. The tools can also provide information for all locations where mission functions are performed.

3.1.3 The vessel design community should continue to track new vessels as they are launched and tested so that trends can be explored, even without the availability of fully validated computational prediction programs.

3.1.4 Ride quality factors such as motion induced interruptions (MII) for SWATH type vessels are likely to be better than for considerably larger displacement monohulls.

3.1.5 Operational limits on SWATH type vessels are likely to be imposed by criteria other than MII, such as hull slamming.

3.2 Recommendations

Recommendations are:

3.2.1 Advances in predictive methods should be pursued via efforts such as that of the NATO Task Group AVT-110. Their objective to "assess the ability to predict the seakeeping characteristics of arbitrary hull forms and the ability to design hull forms to enhance habitability" requires continuing support.

3.2.2 The NATO approach described above should continue as the standard to evaluate and compare the seakeeping performance of all hull types.

3.2.3 Data from various NATO nations' vessel studies and sea trials should be made available for correlation with prediction methods as well as for estimating trends in relative performance.

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Detailed Analysis or Short Description of the AVT-110 contributions and Question/Reply

The Questions/Answers listed in the next paragraphs (table) are limited to the written discussion forms received by the Technical Evaluator. The answers were normally given by the first mentioned author-speaker.

P34 J.H. Pattison, D.J. Sheridan 'Human Performance Factors and Measures in Hull Form Selection', (Noesis, Inc-DJS Associates, Inc, US)

As the most papers of the last session devoted to the naval systems, the focus of this paper is a review of the development of technology for the assessment of human performance factors and measures in a vessel motion environment in order to extract from compared criteria the best vessels hull form. The author concludes on the necessity to pursue the AVT 110 objectives and to get more data from the Nato Countries to assess the design tools.

Discussor's name: J. Hodgdon
Q. You presented a curve showing maximal task performance time versus the rate of oxygen consumption. Do you have comparable curves with no ship motion to allow calculation of the curve of dealing with ship motion?
R. Yes, this is in the work of TNO Human Factors. Contact J.E.BOS (paper 27) for references.

Discussor's name: L.P. Purtell
Q. "Mental tasks" What are they?
R. Decision making tasks include visual coordination and the ability to follow targets on a screen. These are several cognitive performance factors in the paper that address this.